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Healthcare electronics—A step closer to future smart cities

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Abstract

As information and communication technologies are transforming traditional cities into smart cities, the Internet of Things (IoT) makes smart cities efficient and responsive. In retrospect, for medical technologists to enter and establish themselves in the new healthcare industry, it is imperative that we look beyond traditional forms of technological innovations. Hence, IoT is an avenue for consideration. It is hoped that IoT-based healthcare devices will be able to provide the early detection of potential exacerbations and inform patients and medical professionals such that they can be treated promptly. In regard to smart healthcare within smart cities, this paper presents a study where an optoelectronic controller chip was designed to control the micro light emitting diode (LED) matrix used in retinal prosthesis. An individually addressable low-power micro LED array is designed and the results are reported. The chip is fabricated using the German foundry X-FAB 0.35-μm complementary metal oxide semiconductor (CMOS) technology and the total die area is 4 mm^2. It is envisaged that the presented design and technology could potentially be used for a number of applications in healthcare and consumer electronics.

Keywords: Smart cities; Smart healthcare; Retinal prosthesis; Microchip

1. Introduction

The Internet of things (IoT) has numerous applications in healthcare, from remote monitoring to smart sensors and medical device integration. It has the potential to not only keep patients safe and healthy, but also to improve the way physicians deliver care. Healthcare IoT can also boost patient engagement and satisfaction by allowing them to spend more time interacting with their doctors.

As age-related diseases represent one of the most relevant challenges for developing as well as developed countries, using remote healthcare technology may allow the reduction in most of the management of chronic illnesses and may also contribute to the improvement of elderly people's quality of life. Unfortunately, despite the advent of IoT and even the decreasing price of sensors, current proposals are not extensible during runtime because they need to be sufficiently compact, portable, and low power. In this paper, a low-power, compact, and portable vision restoration chip design is reported, which could be mounted on a patient's head to stimulate genetically modified retinal ganglion cells to restore partial vision for patients suffering from diseases such as age-related macular degeneration and retinitis pigmentosa. The three major technologies that are predominantly used to help restore light sensing to partially blind patients suffering from retinal degeneration include namely optogenetics, retinal prosthesis, and photo switches, as stated by Marc, Pfeiffer, and Jones in [1]. While each technology has its own merits and demerits, visual implants in particular require complex surgical procedures with limited resolution. Despite optogenetics-based techniques having much higher resolution, it is still challenging to implement optogenetics-based implants in the human eye. The study presented in this paper is a first step towards the long-term goal of providing a platform and developing fully implantable optogenetics-based visual prosthesis. The author envisages a number of healthcare applications that could potentially benefit from this technology, in particular in patients suffering from Alzheimer's disease and epileptic seizures.

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The wide range of applications where LED arrays are being used include consumer electronics such as LED printers, thin displays in hand-held mobile devices, and electronic equipment for scientific research such as neural stimulation/suppression [2]. The most recent use of micro LED arrays has been reported in biomedical engineering, in particular retinal prosthesis. Micro LED arrays can be used in retinal prosthesis where pixel arrays are used to stimulate genetically modified areas inside the retina of a blind person to restore partial vision [3]. In the context of smart healthcare and visual prosthesis, this paper presents a study where an optoelectronic controller chip was designed to control the LED matrix used in retinal stimulation. To address the individual pixels on a chip, a decoder circuit was designed to decode the input binary address values. The binary input address generated by the decoder is used to select the individual pixel driver cells. A 16 × 16 LED matrix controller chip was designed with pixel pads for 256 micro GaN LEDs. A flip-chip bonding technique is utilized to drive micro LEDs with CMOS drivers. The pixel size was designed with dimensions of 150 μm × 150 μm with a pixel pitch of 70 μm. As the pixel array controller design was intended for stimulating genetically modified neurons, the primary focus of the design was to develop an optimized controller for individually addressable LEDs. The circuit design and chip simulations were performed using the X-FAB 1.35-μm high voltage (HV)CMOS process.

This paper is organized as follows: Section 2 briefly discusses retinal prosthesis and Section 3 elaborates the CMOS micro LED design. The summary is provided in the results/conclusion section of the paper.

2. Retinal prosthesis

2.1. Importance of retinal prosthesis

Currently, there are more than 20 million individuals who suffer from irreversible vision loss due to different gene mutations [4]. The more common retinal diseases are retinitis pigmentosa and age-related macular degeneration [3,4]. In retinitis pigmentosa disorder, the rod photoreceptors are affected and result in tunnel vision and night blindness, which could eventually lead to total blindness. A number of treatments are currently investigated such as optogenetics, photo switches, and prosthetics. Optogenetics is thought to be the most promising technique [5], where genetically modified ganglion cell stimulation is determined by the resolution of the total number of pixels and the power efficiency of micro LEDs. As Channelrhodopsin (ChR2) has a peak sensitivity at 473 nm, for this region of visible spectrum, gallium nitride (GaN) LEDs are able to provide the current density and irradiance to stimulate photosensitized neurons.

In the past, retinal prosthesis employed electrical stimulations similar to cochlear implants. The most recent research efforts have been reported by Chow et al., 2004, Humayun et al., 2012, Klauke et al., 2011, Palanker et al., 2005, and Stingl et al., 2013 [6–10]. Furthermore, in applications such as face recognition and vision, a large number of electrodes (in hundreds) might be required to perform the task. Hence, in contrast to electrical stimulations, stimulations based on the photosensitization of ganglion cells are more promising. However, as this technique is still emerging, an electronic technology is needed to fully understand and exploit its potential before it could be safely deployed for human trials. The following section reports the designed prototype that has the potential to be used as a platform for healthcare technology development, in particular, for retinal prosthesis.

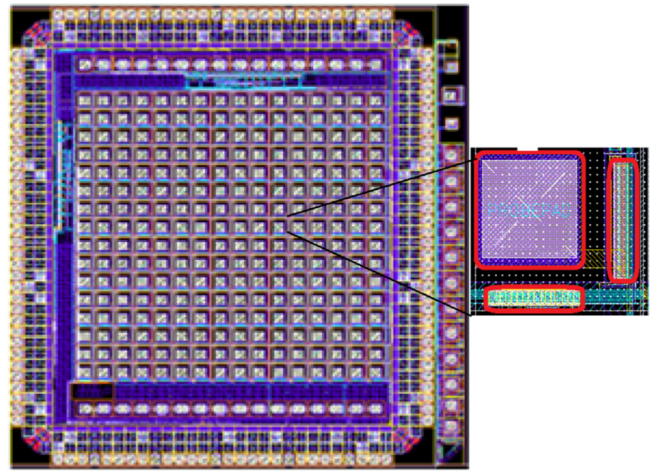

Fig. 1. Micro LED array with pixel layout.

3. CMOS micro LED driver design

To develop a micro LED array to stimulate ganglion cells, a 16 × 16 micro LED array is designed. The computer aided design (CAD) layout is shown in Fig. 1 and the layout of the pixel is shown in the subplot. The chip dimensions are 4 mm × 4 mm, where the individual pixel size measured is 150 μm × 150 μm with a pad size of 80 μm^2 for the solder ball bonding to LEDs. The chip was fabricated using the X-FAB 0.35-μm process. The emission spectrum of the micro LEDs is centered at 470 nm with a 22-nm full width half maximum (FWHM), which overlaps with the peak sensitivity of ChR2. [11].

To modulate the brightness of the LEDs, the pulse width modulation (PWM) technique was employed and the brightness was controlled by changing the pulse width. To shield the electronic circuits and minimize the effect of the emitted light, metal 4 was used. The row/column communication circuits were designed with the minimum number of transistors and the layout area was 916 μm (L) ×106 μm (W). To switch between the serial/parallel modes, 16-bit multiplexers were designed and the layout area was 249 μm (L) ×13.9 μm (W). The layout area for the row decoder was 187.6 μm (L) × 39.4 μm (W). To maintain the memory for each pixel, the layout area for the T flip-flop was 68.55 μm (L) × 16.15 μm (W).

3.1. LED control circuit design

A 16 × 16 micro LED array was designed with CAD tools where a number of CMOS driver circuits were designed

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to quantify the optical efficiency required to stimulate neural response. The LED switching is performed by controlling the gate voltage of the MOS transistor. In retrospect, the LED brightness was controlled by changing the switching speed of the transistor via PWM. Hence, the total voltage delivered to the load is controlled through the duty cycle of the pulse. This technique offers a unique advantage in terms of area because the analog voltage is converted into a digital signal without additional circuitry. The average value of the waveform *f(t)* can be expressed as the maximum value A, minimum value A_0, duty cycle c, and time period T.

$$y = \frac{1}{T}\left(\int_0^T f(t)dt\right) \tag{1}$$

$$y = \frac{1}{T}\left(\int_0^{cT} Adt + \int_{cT}^{T} A_0 dt\right) \tag{2}$$

$$y = \frac{c.T.A + T.(1-c).A_0}{T} \tag{3}$$

$$y = c.A + (1-c)A_0 \tag{4}$$

As the LED brightness depends on the current passing through it, the average value of the signal would be proportional to the duty cycle of the waveform. By assuming a constant sheet resistance of GaN, the current passing through the LED would be directly proportional to the voltage appearing across its terminals. Hence, it is important to ascertain the maximum voltage that could be applied across the LED terminals without any breakdown effects on the control driver circuitry. As the sufficient LED brightness will depend on the maximum voltage that could safely be applied, X-FAB HVCMOS PMOS transistors were used as the drive transistors for chip fabrication. The high-voltage PMOS transistor offers unique advantage because it could withstand voltages up to 45 V without breakdown.

3.2. Power efficiency analysis

As previously demonstrated by [11], the required light intensity to stimulate ChR2 is typically 1 mW/mm^2. An output light power efficiency for a standard GaN LED is approximately 1% of the total electrical power that it consumed. Owing to the dispersion of the light on the LED surface and the power loss due to transmission through air, the overall efficiency of light produced by the LED and the light falls at the top of target neuron and falls again to approximately 1%. To obtain the required power rating of 1 mW/mm^2, the amount of electrical power that needs to be supplied to the LED is approximately 10 W/mm^2.

The diode impedance reduces as the current through the diode increases, hence the voltage drop across the diode is controlled by the sheet resistance of the diode. Therefore, the total impedance of the circuit is calculated by adding the diode impedance and the sheet resistance of the transistor. The sheet resistance of the PMOS transistor under test is 108 Ω. Fig. 2 shows the variation in output power for the different sheet resistances of the transistor. Fig. 2 shows that no significant changes occurred in the power with the change in the sheet resistance for the normal working voltage of the Micro LED array below 15 V.

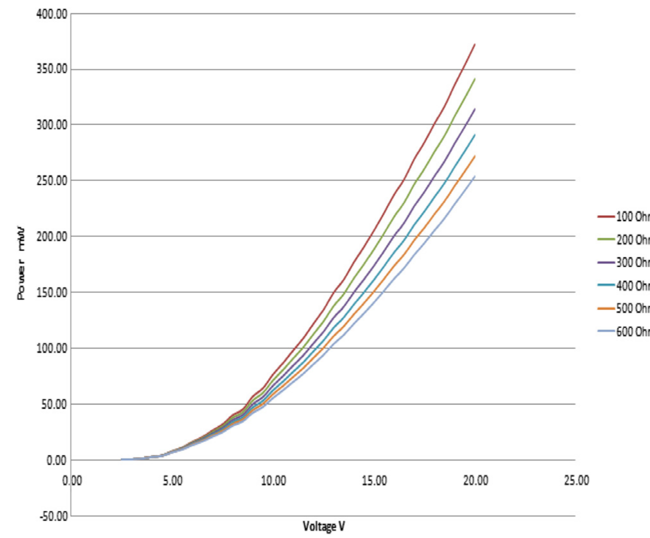

Fig. 2. Output power (mW) vs. voltage (V) and sheet resistance (Ω).

3.3. Control pixel

To analyze the power performance of the micro LEDs, a number of drive circuits were tested; however, the single HVPMOS (XFAB) was found to be better suited to control the LED in terms of maximum breakdown voltage. The circuit designed allows maximum voltage across the transistor and in turn across the LED pixel. Therefore, the single transistor circuit is chosen to control the LEDs in the LED matrix chip. The LED array comprising of a matrix structure of LEDs, is fabricated in a GaN substrate and is flip-chip bonded to the control chip. The control chip of individual pixels acts as the current source for the LEDs. The PMOS transistor can thus be integrated as an element of the individual pixel in the control chip. The components of the control chip are a T flip-flop and a PMOS LED driver transistor. The T flip-flop was used to retain the memory state for keeping the LED *ON* and *OFF* according to the requirement. A series of Zener diodes were included to remove the static charge buildup during flip-chip bonding.

As each pixel is required to be individually controllable, when a specific pixel is selected, an electronics circuitry should supply voltage to the PMOS transistor, which turns ON the LED. When the control signal that selects the pixel is removed, the LED should stay in the ON state and should turn OFF when the pixel is selected again. Therefore, the circuit needs a memory element to hold its current state. A T flip-flop is introduced to toggle its state each time it is clocked such that it can be used to turn ON/OFF the PMOS transistor. The top-level circuit diagram of the control pixel is shown in Fig. 3.

3.4. Addressing modes

To fully control an individually addressable micro LED array, four different addressing modes were implemented, namely fully serial, fully parallel, row serial–column parallel, and column serial–row parallel. The primary purpose of the different

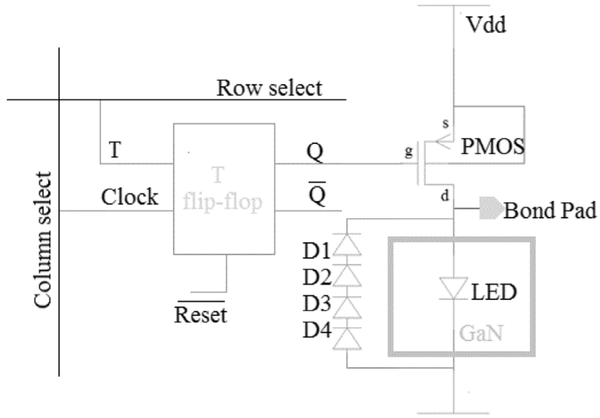

Fig. 3. Top-level circuit diagram of pixel.

addressing modes was to control the LED pixels with different speeds to address the requirement for neural stimulation. Two communication decoders were implemented on the top and left sides of the control chip. As the 16 × 16 LED matrix had sixteen rows and sixteen columns, a 4-bit binary address decoder was designed. The input to the decoder is a 4-bit binary address with sixteen output lines corresponding to the input binary addresses.

3.5. Optoelectronic control chip simulations

The main components of the optoelectronic control chip are the individual pixels and address decoders. The pixels are connected across the row and column outputs of the address decoders. To select any individual pixel, the row and column binary address of the pixel is provided to the inputs of the address decoders. The corresponding row and column for the given inputs will go high as soon as the inputs are applied. This will select the pixel connected to the row and column, which is the T flip-flop inside the individual pixel. The T flip-flop toggles the output from its previous value by turning the control transistor ON or OFF, which in turn switches the LED ON or OFF depending upon the previous state. The chip-level simulation results are shown in Fig. 4.

3.6. Heating profile and limitations

To improve the performance parameter of the micro LED arrays, it is essential to develop ultra-bright LEDs. Hence, it becomes critical to devise effective heat dissipation strategies. High brightness requires high current densities, which in turn produces more heat. In micro LED arrays, it is important that the light output power from a single emitter is increased. This can be achieved by increasing the emitting area and injection current. However, these changes do not increase the optical output power significantly because of the device's self-heating. It was observed that keeping the array ON for longer periods produces localized self-heating, which is undesirable from both the performance and healthcare applications perspective. A very high localized temperature of the device could damage cells and tissues primarily because of the self-heating arising at the p-contact of the LED surface. This overheating in turn reduces the light output power and the wall-plug efficiency. Hence, the heating of the device causes reduced performance, and a spectrum shift [12]. To address this problem, a Peltier cooler was attached to the chip surface whereas the temperature profile with respect to the Peltier voltage is as shown in Fig. 5. The latter shows a significant improvement where the surface temperature of the chip was reduced by increasing the Peltier voltage.

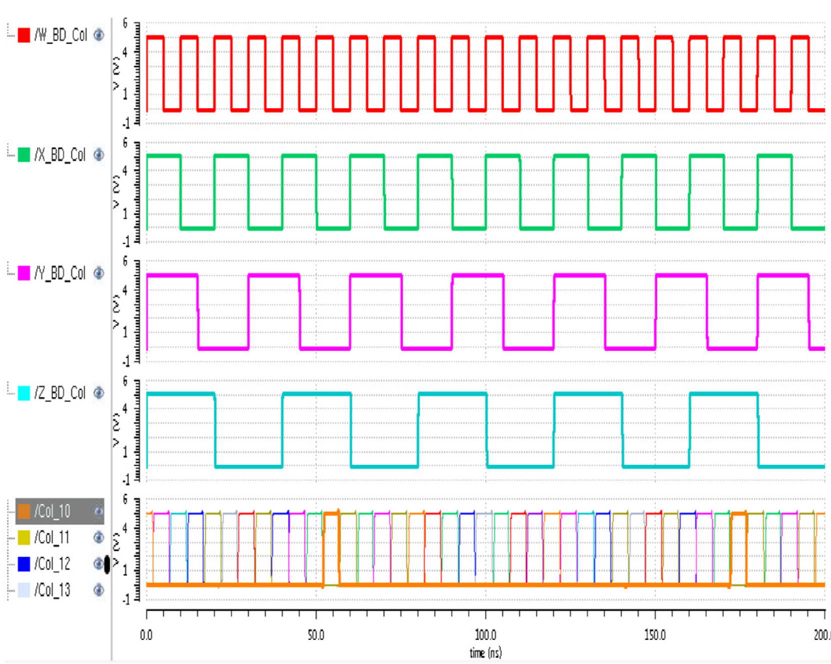

Fig. 4. Generation of 4-bit addresses through direct mode (top four traces) to select individual LEDs in a 16 × 16 array (shown in the bottom trace).

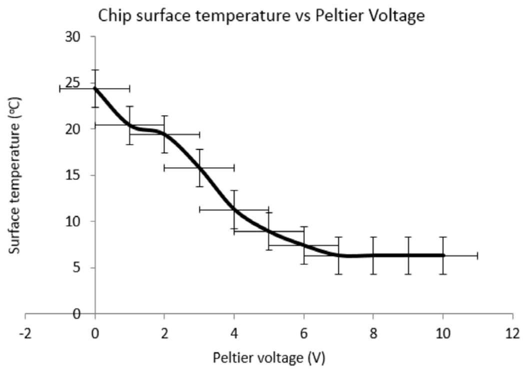

Fig. 5. Chip surface temperature vs. Peltier voltage.

4. Results/conclusion

In this paper, a control chip was designed and fabricated using a 0.35-μm CMOS process from X-FAB—a German foundry, to develop a platform and stimulate retinal ganglion cells. This involved both low-level driving circuits and high-level communication circuitry. An active bi-stable circuitry was implemented with low-access RC time constants. Key to this circuit is the required driving current for the micro LED. As the output transistor has high source–drain impedance, it was required to drive up to 9 V. High-voltage transistors have large impedances, which in turn reduce the efficiency of the combined driver/LED. The drive lines were designed to provide sufficient power while negating electromigration issues. As the long-term use of the chip requires that the micro LEDs remain ON for longer periods, heat dissipation becomes a dominant factor. To address this issue, a Peltier cooler was custom designed and attached to the surface of the chip to keep it cool. We observed significant improvement in terms of surface temperature and Peltier voltage.

Conflict of interest

The authors declare that there is no conflict of interest in this paper.

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